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14. ABSTRACT
The efforts during the project period had been directed to solving of several fundamental problems which are critical to a successful invention of new THz nano-sensors and spectral analyzers. The basic problems which we had solved theoretically within the project were as follows. (i) The THz field induces the electron transport on nanoscale which requires new approaches. (ii) The elementary excitations in the CNT are not mere electrons and holes as it is in regular semiconductors. They are rather quasiparticles which are characterized by chirality and pseudospins. (iii) The electron transport occurs through numerous potential barriers of arbitrary transparency along and in-perpendicular to the CNT axis. Therefore its adequate description requires special methods. (iv) The THz field which acts on the CNT quantum well might have an arbitrary intensity. The aforementioned problems (i)-(iv) had to be accomplished theoretically which was the purpose of the theoretical research within the project. Another purpose of the theory was to interpreting of the experimental data obtained by the partner Georgetown group (Prof. P. Barbara).

15. SUBJECT TERMS
carbon nanotube field effect transistors, quantum well arrays, THz nano-sensors, spectral analyzers.

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Title: Sensing the THz field by an array of carbon nanotube quantum wells.
PI: Serhii Shafraniuk, Northwestern University
Final report for the period April 1 2009 – July 31 2012

The aim of our research work during the project period was facilitating of new approaches for sensing and spectral analyzing the THz field based on arrays of carbon nanotube quantum wells. The carbon nanotubes (CNT) and graphene belong to a new class of materials. Technological and experimental progress in this new field of research is strongly dependent on coherent and adequate understanding the basic mechanisms of interacting the external THz field and the carbon nanotube quantum wells. A mere application of known orthodox models which were elaborated for conventional semiconductors and metals causes confusion and is incorrect. Therefore our theoretical efforts during the project period had been directed to solving of several fundamental problems which are critical to a successful invention of new THz nano-sensors and spectral analyzers. The basic problems which we had solved theoretically within the project were as follows. (i) The THz field induces the electron transport on nanoscale which requires new approaches. (ii) The elementary excitations in the CNT are not mere electrons and holes as it is in regular semiconductors. They are rather quasiparticles which are characterized by chirality and pseudospins. (iii) The electron transport occurs through numerous potential barriers of arbitrary transparency along and in-perpendicular to the CNT axis. Therefore its adequate description requires special methods. (iv) The THz field which acts on the CNT quantum well might have an arbitrary intensity. Therefore the interaction mechanism cannot be simply described in a conventional assumptions of a weak a.c. field as was used before. To elaborate recommendations for nanotechnology and for the experiments and to interpret the experimental data one needs to use new methods which were elaborated in this project. The aforementioned problems (i)-(iv) had to be accomplished theoretically which was the purpose of the theoretical research within the project.

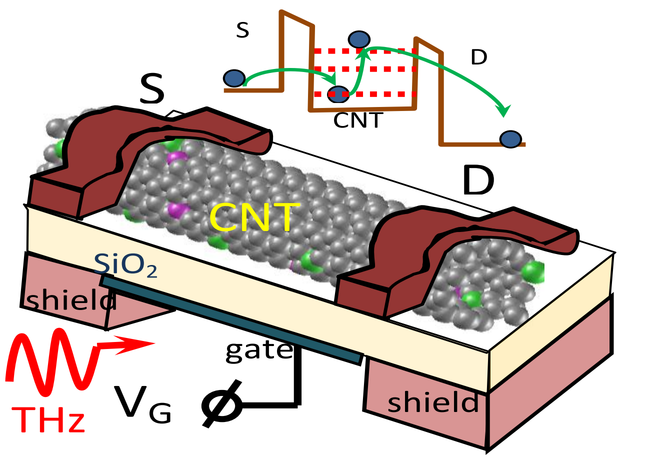


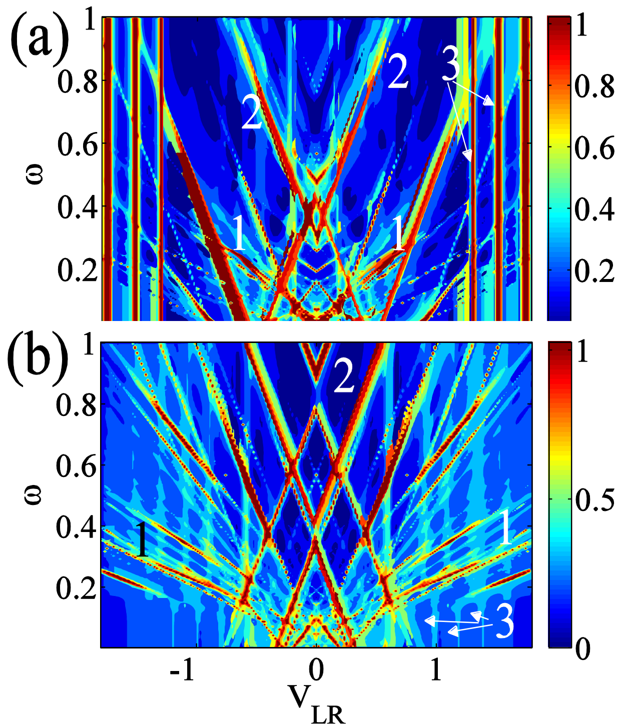
Fig. 1. The carbon nanotube THz field sensor element. The energy diagram is sketched at the top.

Another purpose of the theory was to interpreting of the experimental data obtained by the partner Georgetown group (Prof. P. Barbara). In our work we studied sensing mechanisms of the THz field of arbitrary amplitude by an array of carbon nanotube (CNT) quantum wells. Our efforts had been focused on the resonant a.c. transport in the field effect CNT transistors exposed to an external THz field. The a.c. transport phenomena had been examined in a configuration where an a.c. gate voltage adjusts the electrochemical potential μ in the central CNT section. The a.c. field influence on properties of the carbon nanotube quantum wells had been accounted for by the Floquet method. The Floquet technique which exploits the periodic time dependence of the external field is a non-stationary analog of the Bloch theorem for solid state crystals. Our approach permits reducing of a non-stationary problem to a stationary task which in our case is solved analytically and numerically. We found that the electron propagation along the junction is quantized, so the setup is a quantum well with discrete energy levels. We examine how the a.c. field affects the level quantization versus the field frequency and field amplitude. We find that an a.c. field changes the transport through the junction dramatically which is reflected in the junction′s differential conductivity.

Besides we examined a carbon nanotube heterojunction which also works as a low-noise THz sensor cell. In the heterojunction, the central CNT section is suspended and has a bigger diameter than the CNT ends. Our idea was to reduce the thermal noise coming from the external electrodes and from the SiO_2 substrate. The central CNT section with the bigger diameter serves as a quantum well while the CNT ends serve as electrodes. We expect that the amount of thermal noise disturbing our quantum well due to emerging phonons will be much lower as compared to the formerly studied CNT THz sensor devices. An apparent advantage of such a heterojunction sensor is the thermal separation of the suspended central CNT section from the substrate. Another benefit is in the CNT electrodes which emit considerably less amount of phonons than metallic electrodes: the electron recombination there creates much lower phonon flow. Therefore the intrinsic noise in the central nanotube section along with the noise emerging from attached carbon nanotube electrodes is depleted. The depletion mechanism originates from so-called chirality conservation taking place in carbon nanotubes and graphene. The mentioned phenomena had been studied within our theoretical model which describes the a.c. transport across the carbon nanotube hererojunction.

In the work we computed the level width and spacing, and the coupling strength between the adjacent electrodes. We also studied how the external electromagnetic field affects dynamics and inter-level transitions in the system of two quantized states. We computed basic characteristics of the two level system (TLS) including the upper level population and the field-induced magnetic moment. Using obtained results we examined the intrinsic noise and the noise emerging from adjacent electrodes. In particular we calculate the level broadening due to the electron-phonon interaction and the spectrum of thermal phonons generated due to electron-phonon collisions which are the major source of the intrinsic thermal noise. This allows to establish necessary conditions when the quantum well is “quiet”. Our study had been also focused on the Johnson–Nyquist noise and the shot noise.

During the project period our purpose was also to examine the photon-assisted single electron tunneling (PASET) using an upgraded theoretical model based on Green Keldysh functions for non-equilibrium processes. Our upgraded model describes the PASET transport through the FET with attached source and drain electrodes. The device which poses as a quantum well is sketched in Fig. 1. The CNT quantum well is formed by a section of single wall carbon nanotube resting on a dielectric SiO_2 substrate (see Fig. 1). The carbon nanotube (CNT) section has typical length $L_T =$250-5000 nm and is enclosed between two metallic electrodes S and D deposited at the top of the CNT. Since concentrations of the electric charge carriers in the metallic electrodes and in the CNT section differ, the interface Schottky barriers arise. The barriers are located right at the interfaces between the metallic electrodes and the CNT (see inset in Fig. 1). If the nanotube is free of defects and atomic impurities, the electron motion inside the CNT section is ballistic. Interference between incident electron waves with the waves backward reflected from the Schottky barriers causes the electron motion inside the CNT section to be quantized. The corresponding spacing Δ between two adjacent quantized energy levels is $\Delta = 2hv / D_T$ where D_T is the tube length. The gate electrode is placed underneath of the dielectric SiO_2 substrate as shown in Fig. 1. In this way, the quantum well is formed inside the CNT section enclosed between the two Schottky barriers. The whole setup represents a field effect transistor (FET) where the metallic electrodes S and D serve as source and drain. The gate voltage V_G controls the quantized level (red dash in Fig. 1) positions while injecting of electrons from the S and D electrodes into the CNT changes population of the levels. The interface capacitance between the metallic electrodes and the CNT section is small, so the Coulomb staircase is pronounced in the d.c. steady state current voltage characteristics (when the external a.c. field is off). When the external THz field is on, the Coulomb staircase is modified. Our task was to creating of the model which explains and decodes the mentioned THz field influence on the d.c. I-V curves. The decoding of the d.c. curves will be then used for determining of the external THz field parameters.



The contour patterns $G(\omega,V_{LR})$ for non-chiral (a) and chiral (b) electron transport in the CNT section T. The a.c field amplitude in both the cases is U_1 = 0:3. The junction geometry, a.c. field parameters, and units are in $10^{-2}\Delta$ (VHS spacing).

The theoretical model developed during the project period describes the THz field-induced electron transport across the carbon nanotube hererojunction in conditions of the photon-assisted single electron tunneling induced by the external THz field. Our results indicate that the resonant a.c. transport strongly depends on the polarity and magnitude of the source-drain and gate voltages. The voltages tune the basic a.c. transport properties of the carbon nanotube field effect transistor by affecting of the CNT electronic structure and of the phase-correlated transport of charge carriers. Due to resonant character of chiral tunneling and low inelastic scattering rates the a.c. current density can be much higher than in ordinary semiconducting devices. The a.c. transport phenomena show great promises for detector arrays of the external THz field. Besides, they have a good potential for probing of various many body phenomena including excitons and the Luttinger liquid state which will potentially extend the frequency range of the THz detectors.

We obtained theoretical and numeric results of our study the THz field detector array based on the carbon nanotube (CNT) quantum well (QW). The CNT QW detector exploits a change in the conductance of the CNT quantum well when the THz field is applied. We also examined resonant properties of the quantum well based on the CNT field effect transistor (FET). Two major phenomena are involved: (i) Formation of the quantized states in presence of the THz field; (ii) Photon-assisted single electron tunneling. Our results indicate that by implementing of either the above phenomenon provides a good detector responsivity $R = \Delta V_{SD} / SP_s = 10^6$ V/W which is much higher than a typical responsivity of the Schottky diode THz detectors ($R_{Sh} = 10^3$ V/W). Even much better responsivity $R = 10^8 - 10^9$ V/W might be achieved when combining of the two aforementioned phenomena (i)+(ii). This combined approach is practiced by my partner experimental P. Barbara group (Georgetown University). My theoretical model had been used for supercomputer simulation to fit the experimental data obtained in the aforementioned group.

We conclude that the CNT THz detector has a superb sensitivity, a tiny size and is tunable dynamically. The nanotube-based THz detectors show a strong potential for variety of applications including defense, security, nanoelectronics, chemistry, industry, and medicine.

Possible applications of obtained results include the THz receivers/spectral analyzers, the THz field antennas, and the electromagnetic wave and acoustic transmitters. The obtained results make also possible extracting of the THz field parameters from the d.c. characteristics of the carbon nanotube field effect transistors. It allowed the analyzing and interpreting of the experimental results obtained by the partner P. Barbara group at Georgetown University.

Future’s plans involve a thorough patching the THz domain diapason by varying the junction’s geometry, transparency, and the tube chirality along with further reduction of intrinsic and parasitic noises and improving the analyzer overall sensitivity at room temperatures.

Accomplishments

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